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Effect of temperature difference load of 32 m simply supported box beam bridge on track vertical irregularity

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Abstract In order to study the effect of temperature difference load (TDL) along the vertical direction of a simply supported beam bridge section on the vertical irregularity, a rail-bridge-piers calculation model was established. Taking 32 m simply supported box beam bridge which is widely used in the construction of passenger dedicated line in China as an example, influences of the temperature variation between the bottom and top of the bridge, temperature curve index, type of temperature gradient, and beam height on track vertical irregularity were analyzed with the model. The results show that TDL has more effects on long wave track irregularity than on short one, and the wavelength mainly affected is approximately equal to the beam span. The amplitude of irregularity caused by TDL is largely affected by the temperature variation, temperature curve index, and type of temperature gradient, so it is necessary to monitor the temperature distribution of bridges in different regions to provide accurate calculation parameters. In order to avoid the irregularity exceeding the limit values, the height of 32, 48, and 64 m simply supported box beam bridges must not be less than 2.15, 3.2, and 4.05 m, respectively.

Keywords Simply supported beam bridge · Temperature gradient · Vertical irregularity · Beam height

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1 Introduction

Simply supported beam bridges are widely used in the construction of passenger dedicated lines in China because of their characteristics of simple structure, clear path for force transfer, low cost, easy manufacturing and installing techniques [1, 2]. After long-term research in design and application, the system of simply supported beam bridges (20, 24 and 32 m in span) for Chinese passenger dedicated line was formed [3–4]. According to statistical data, the total kilometrage of simply supported beam bridges is more than half of the total length of high-speed railways in China, and the most widely used is the 32 m simply supported beam. Thus, ensuring the service performance of continuous welded rail (CWR) on the simply supported beam bridge is essential for safe operation of railways.

Due to solar radiation, temperature distribution along the vertical direction of a simply supported beam bridge section is nonuniform, which would cause warping deformation of bridge. The deformation causes vertical displacement and additional longitudinal force of rail because of the interaction between bridge and track. The increased longitudinal force affects the strength and stability of CWR [5, 6], and vertical displacement of rail causes vertical irregularity, thus affecting the riding comfort of vehicles.

In some extreme conditions, the vertical displacement and longitudinal force both become large, and result in buckling of track. Researchers such as Tao et al. [7], Ye et al. [8], and Lee [9] expatiated on the temperature distribution of bridge. Kumar et al. [10] found that temperature difference load (TDL) could significantly increase the longitudinal force of rail under the assumption that temperature was distributed linearly along the vertical direction of a bridge section, and hence suggested that the impact of TDL should be considered into the design of CWR on bridge. An et al. [11] studied the effect of TDL on the additional expansion and contraction force of CWR. These studies, however, only considered the effect of TDL on longitudinal force of rail, but ignored the effect of load on the vertical displacement of rail.

In this paper, a rail-bridge-pier integrated model was established taking the temperature distribution along the vertical direction of simply supported beam bridge section into consideration. Taking the 32 m simply supported box beam bridge as an example, the effect of TDL on the displacement of rail on bridge was investigated.

2 Calculation model

2.1 Model establishment

According to the interaction between bridge and track [12], a rail-bridge-pier integrated calculation model as shown in Fig. 1 was established. The model would take the temperature distribution along the vertical direction of the bridge section into consideration.

In the model, rail was simulated with Euler beam element. In order to consider the effect of distribution of temperature along the vertical direction of the bridge section and reduce the computing time, the bridge was meshed into shell elements. Nonlinear spring element was adopted to simulate the vertical and longitudinal stiffness of fasteners. Linear spring element was used to imitate the stiffness of piers. The model only considered the vertical bracing of the movable support, ignoring its longitudinal restraint [13, 14].

In order to reduce the effect of boundary conditions on calculation results and make sure that CWR on bridge is in the fixed zone, the length of subgrade should be 200 m in the following calculation.

2.2 Calculating parameters

Several dozens or hundreds of simply supported beam bridges are usually laid one by one, so reasonable simplifications are needed in the calculation. During the analysis, ten-span 32 m simply supported beam bridges were used as shown in Fig. 2. The fixed supports are laid on the left of beams; the other side are movable supports.

The values of longitudinal horizontal stiffness of abutments and piers are based on the Code TB/100012-2012 [15], 3,000 kN/cm for abutments and 350 kN/cm for piers. The structure of bridge section is referred to as "post-tensioned concrete simply supported box beam bridge for ballastless track of passenger dedicated line at a speed of 250 km/h," and the beam height is 2.6 m. The cross section of the simply supported box beam bridge is shown in Fig. 3.

The parameters of temperature distribution along the vertical direction of the bridge section are taken by the Code TB/100023-2005 [16]: the temperature gradient obeys an exponential distribution, which is as follows:

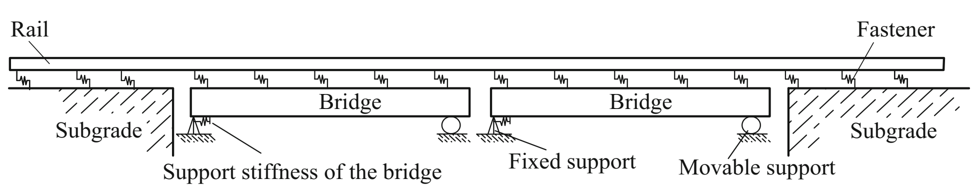

Fig. 1 Rail-bridge-piers integrated model

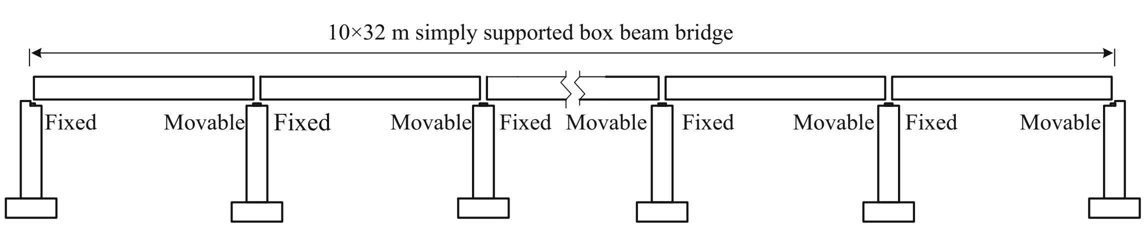

Fig. 2 Arrangement of bridge spans and bearings

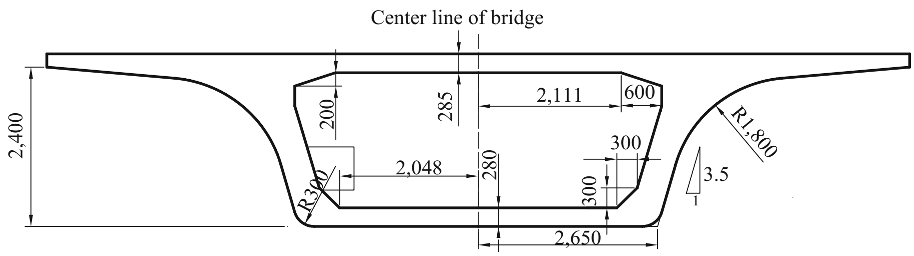

Fig. 3 Cross section of simply-supported box beam (unit: mm)

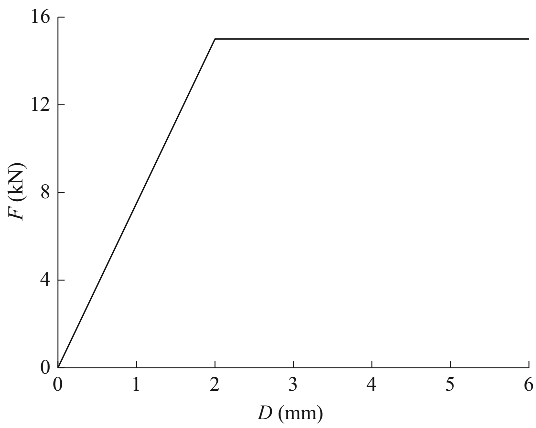

Fig. 4 Longitudinal resistance of fastener

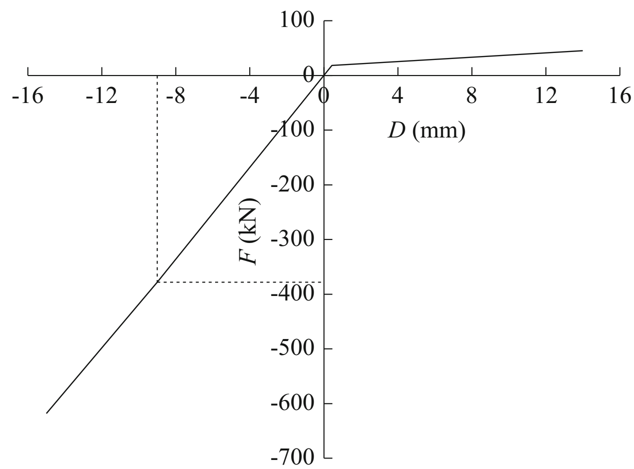

Fig. 5 Vertical resistance of fastener

$$T_y = T_0 \mathrm{e}^{-ay}, \tag{1}$$

where T_y, T_0, a, and y denote the temperature variation at the calculation point, the temperature variation between the bottom and top of the beam, temperature curve index, and the distance between the calculation point and the top of the bridge, respectively. In the Code, T_0 and a are taken as 20 °C and 5 m^{-1}, respectively.

Fasteners used on the bridge are normal resistance type. The longitudinal *D*–*F* curve (Fig. 4) of fasteners between longitudinal displacement and resistance force is taken by Code [15], and the vertical one is the same as that in [17] (Fig. 5), where *D* is the relative displacement between bridge and rail, and *F* is the resistance of a fastener.

3 Basic condition

The longitudinal force and displacement of rail under the basic load were calculated to discuss the effect of TDL on CWR on bridge. The results are shown in Fig. 6, where x is the distance from the left abutment, λ is irregularity wavelength, and PSD stands for the power spectral density.

We can see from Fig. 6a that the TDL of the bridge has an influence on the longitudinal force of the rail. The temperature variation between the bottom and top of the beam causes a longitudinal displacement of top flange, and resulting in a longitudinal force in the rail through the interaction between bridge and track. However, the value of the force is relatively small. As shown in Fig. 6b, c, and d, the vertical displacement of rail, the 10 m-chord versine alignment value, and the 5 m-alignment value of 30 m chord are cyclically changed. The results of Fig. 6c–e show that TDL has made more effects on the long wave track irregularity than on the short one, and the wavelength mainly affected is approximately equal to the beam span, as the second peak point of Fig. 6f shows. The spectrum of irregularity near the wavelength of beam span has exceeded the amplitude of German railway spectra of low irregularity (GRSLI).

4 Analysis of influencing factors

This part mainly analyzes the effects of temperature variation, temperature curve index, type of TDL, beam height, and beam span on the vertical displacement of rail and track irregularity caused by TDL.

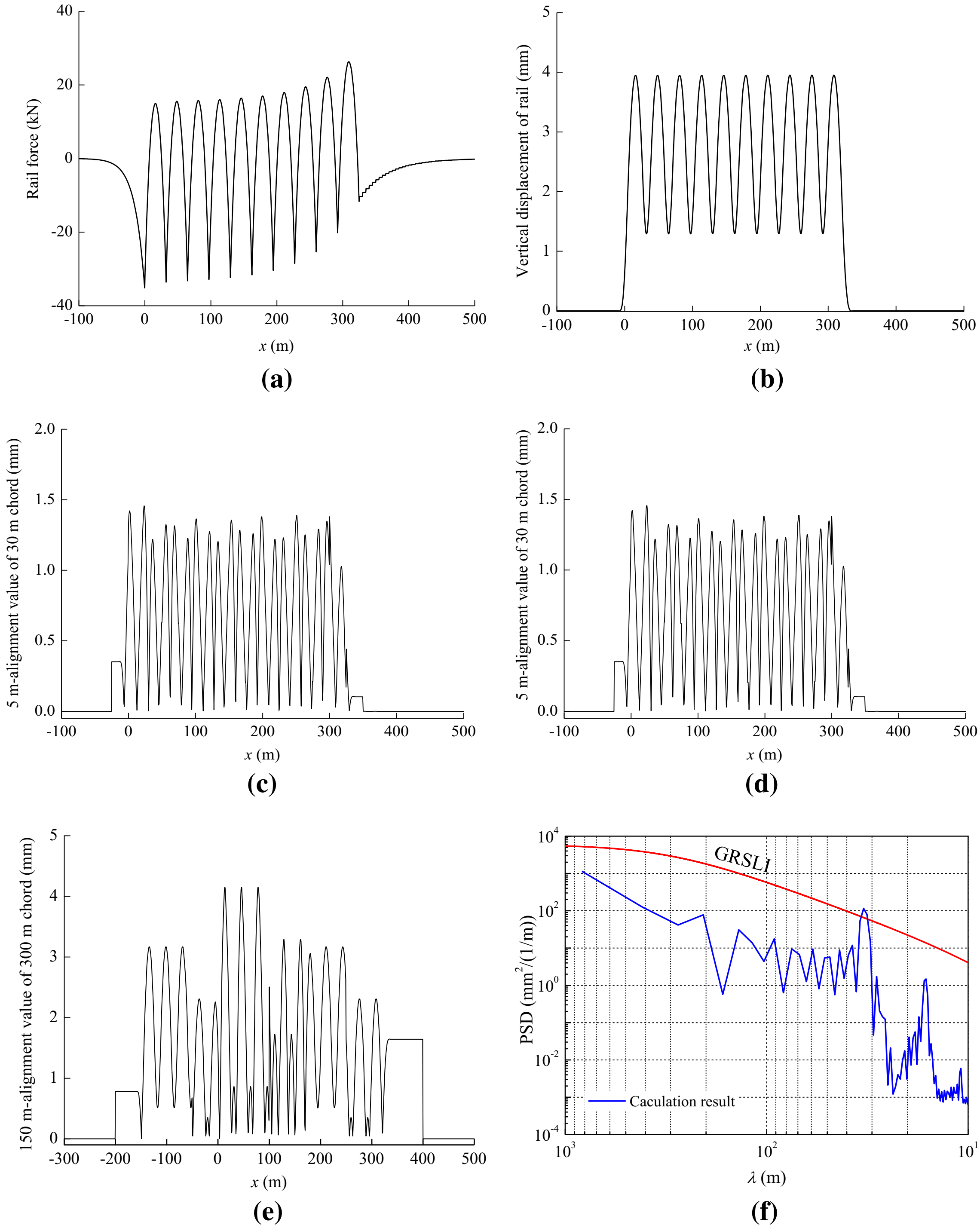

Fig. 6 Results under the basic condition: **a** Longitudinal forces of rail. **b** Vertical displacement of rail. **c** 10 m-chord versine. **d** 5 m-alignment value of 30 m chord. **e** 150 m-alignment value of 300 m chord. **f** Track spectra

4.1 Temperature variation

The Code [16] states that the temperature variation between the bottom and top of bridge is 20 °C when only vertical temperature gradient is considered. However, since China has a vast territory, temperature variations are different when bridges are laid in different directions and regions. Therefore, it is necessary to study the effect of temperature variation on the displacement of rail. The value of temperature variation ranges from 5 to 25 °C with

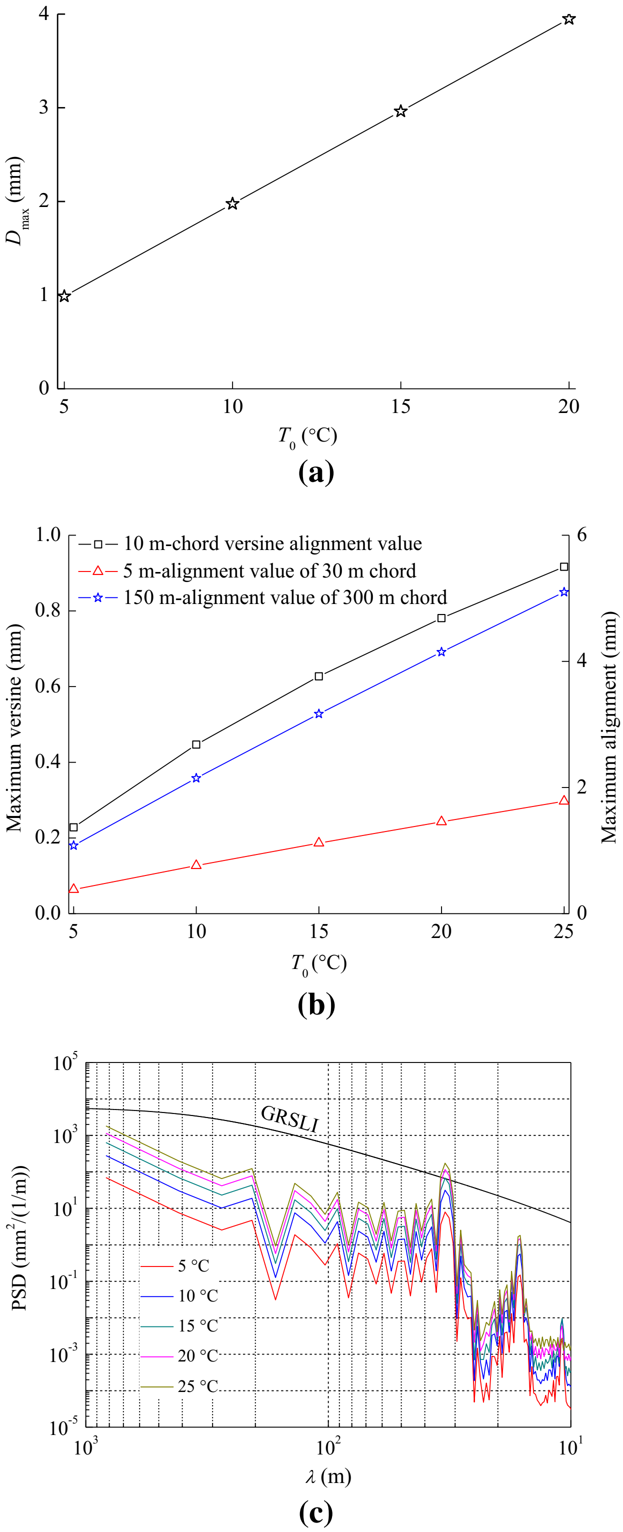

Fig. 7 Results for temperature variation: **a** Vertical displacement of rail. **b** Irregularity versine and alignment. **c** Track spectra

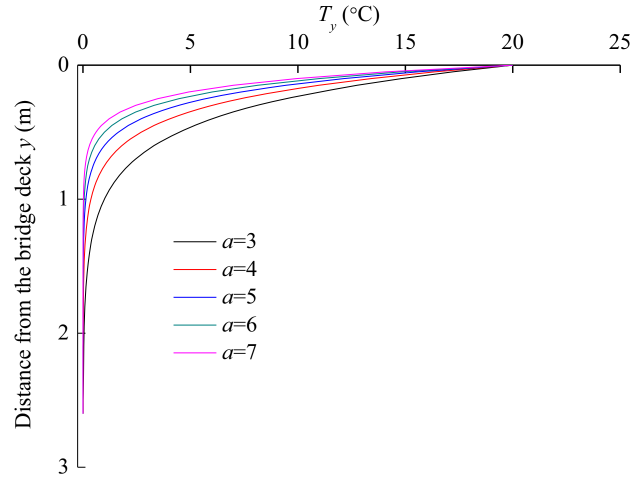

Fig. 8 Temperature distribution

an interval of 5 °C. The results are shown in Fig. 7, where D_{max} is the maximum vertical displacement of rail.

As shown in Fig. 7, the maximum vertical displacement of rail increased linearly along with the rise of temperature variation. When the amplitude of temperature variation is 25 °C, the 5 m-alignment value of 30 m chord is 1.8 mm, close to the limit value of 2 mm, but the 10 m-chord versine and the 150 m-alignment value of 300 m chord are both far away from limit values. Therefore, the control index is the 5 m-alignment value of 30 m chord. Figure 7c shows that the variation tendency of PSD in different conditions is similar. Amplitudes of PSD at the same wavelength decrease with the fall of temperature variation, but the wavelengths corresponding to the peak point do not change. This proved that the irregular wavelength is mainly affected by the bridge span.

As shown in Fig. 7, when temperature variation is not less than 20 °C, the amplitudes of PSD corresponding to 32 m wavelength nearby exceed the value of GRSLI, which will influence the riding comfort. Therefore, the monitoring of track irregularity caused by TDL should be strengthened, and large displacements of rail should be adjusted in time to avoid track's vertical irregularity exceeding the limit value.

4.2 Temperature curve index

Temperature curve index affects the rate of temperature drop along the vertical direction of the beam section. Temperature curve indexes in related references [7, 8] are different from that specified in the Code [16], and they

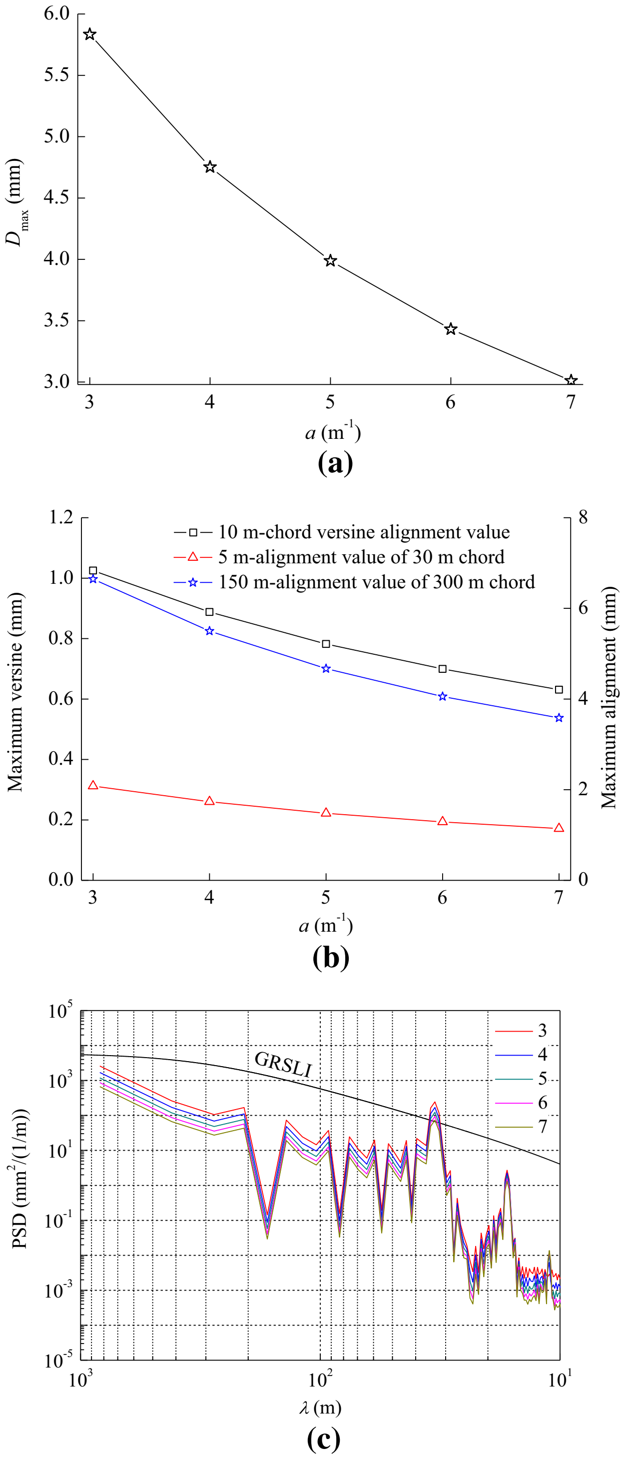

Fig. 9 Results for different temperature curve indexes: **a** Vertical displacement of rail. **b** Irregularity versine and alignment. **c** Track spectra

are smaller than the latter. Therefore, it is necessary to address the impact of temperature curve index on the track vertical irregularity. In the calculation, temperature curve

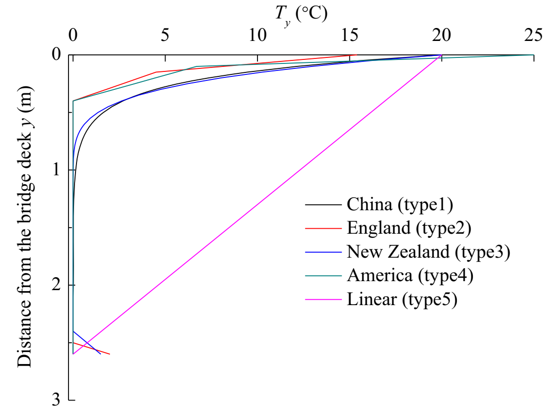

Fig. 10 Different types of temperature gradient

indexes are 3, 4, 5, 6, and 7 m^{-1} respectively, and the temperature distribution along the vertical direction of the beam is shown in Fig. 8.

We can see from Fig. 8 that a smaller temperature curve index will cause a faster drop of the temperature along the beam height. The calculated results are shown in Fig. 9.

As can be seen from Fig. 9, with the increase of temperature curve index, the maximum vertical displacement of rail, 10 m-chord versine, 5 m-alignment value of 30 m chord, 150 m-alignment value of 300 m chord, and the amplitude of PSD all decrease gradually, but the rate of decreasing slows down. From Fig. 9b, when the temperature curve index is 3 m^{-1}, the corresponding 5 m-alignment value of 30 m chord has already exceeded the limit value 2 mm. From Fig. 9c, even when the temperature index is 7 m^{-1}, the amplitude of PSD corresponding to 32 m wavelength nearby exceeds the value of GRSLI.

Obviously, temperature curve index has a great effect on irregularity. The accuracy of temperature curve index directly affects whether the calculation results overrun the limit values. Thus, it is necessary to monitor the temperature distribution of beam in different regions and different natural environments, so as to provide accurate parameters for subsequent calculations.

4.3 Type of temperature gradient

Bridge design codes of different countries differ from each other in the temperature gradient along the vertical direction of bridge section. The differences mainly display in temperature variation and temperature distribution. For example, norms of Britain, America, and other countries [18, 19] state that the type of temperature distribution is folding line, while the standard of New Zealand [20] stipulates that the type is a five power function. Meanwhile,

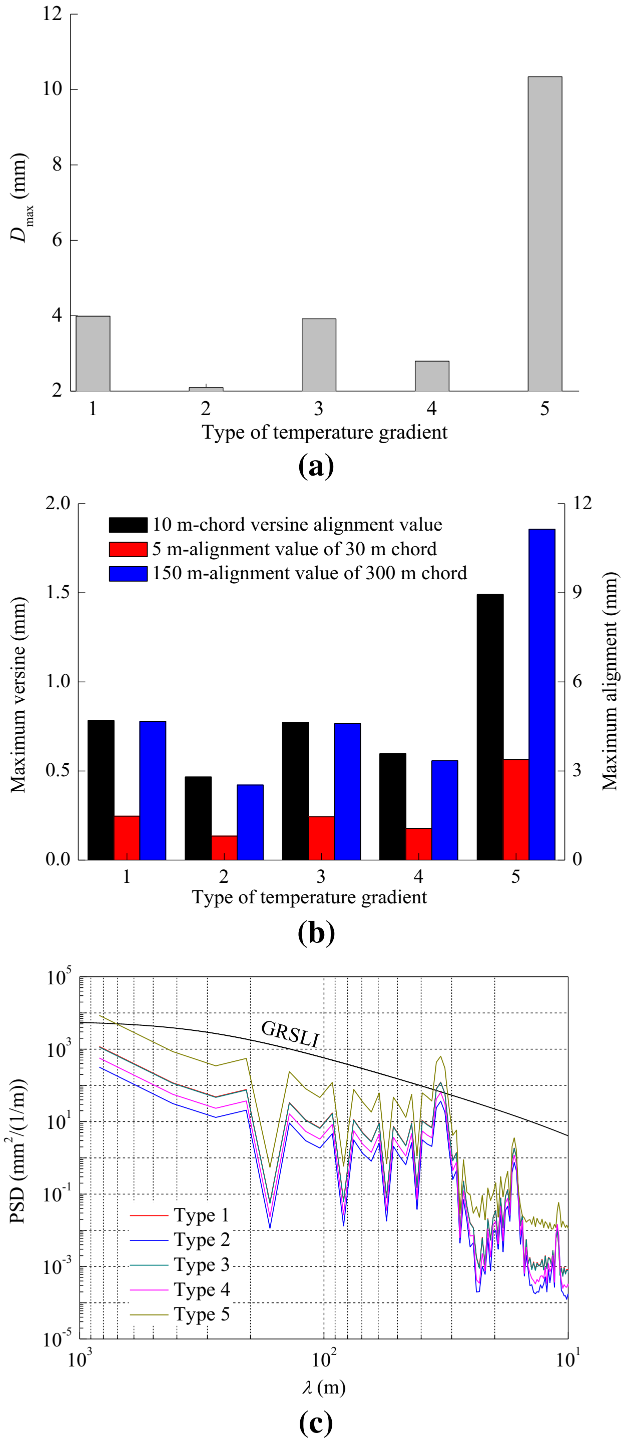

Fig. 11 Results for different types of temperature gradients: **a** Vertical displacement of rail. **b** Irregularity versine and alignment. **c** Track spectra

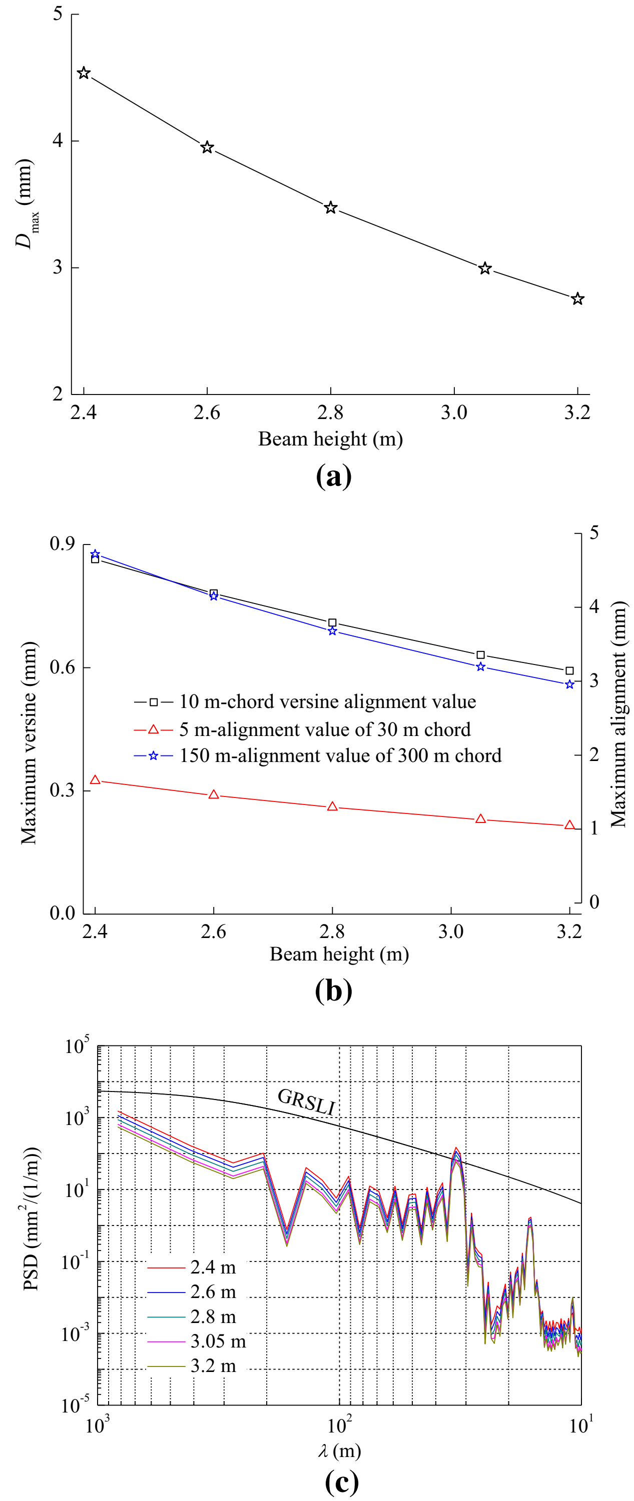

Fig. 12 Results for different beam heights: **a** Vertical displacement of rail. **b** Irregularity versine and alignment. **c** Track spectra

these norms all consider the negative temperature gradient in a certain range of the beam bottom. The corresponding temperature distribution is shown in Fig. 10. Type 5 is a hypothetical case whose temperature distribution is linear, and the negative temperature gradient is ignored. The parameters of type 2 are selected according to zone 2.

From Fig. 10, one can see that the changing trend of temperature gradient of China is approximately the same as

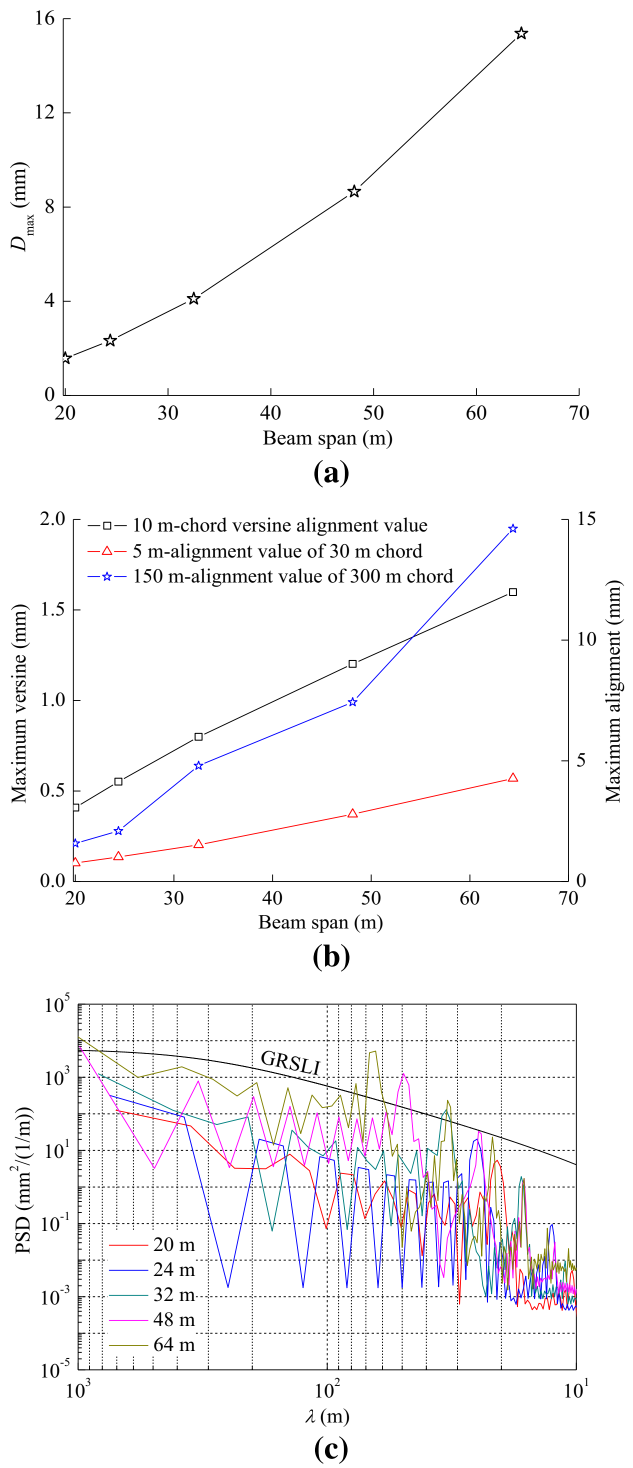

Fig. 13 Results for different beam spans: **a** Vertical displacement of rail. **b** Irregularity versine and alignment. **c** Track spectra

those of New Zealand, England, and America, but the beam surface temperature used by England and America is quite different. Figure 11 shows the calculation results under five types of temperature gradients.

Since type 2 with the temperature variation of 15.4 °C is the smallest in Fig. 11, the corresponding rail displacement and irregularity are also the smallest. Although type 4 has the maximum beam surface temperature of 25 °C, the vertical displacement of rail and irregularity do not reach the maximum because of the impact of temperature distribution (the change rate of temperature along beam height is moderate). As the temperature variation and temperature distribution along the beams of types 1 and 3 are quite similar, the differences of the maximum vertical displacement of rail and irregularity amplitude between the two are minor. The change of temperature distribution of type 5 is the intensest, so the corresponding vertical displacement of rail and irregularity are the largest among the five types. The 5 m-alignment value of 30 m chord and the 150 m-alignment value of 300 m chord exceed their limit values of 2 and 10 mm, respectively, and the amplitude of PSD corresponding to the 32 m wavelength nearby exceed the value of GRSLI.

From the above analysis, the impact of the temperature distribution has a large impact on the vertical displacement and vertical irregularity of rail. Therefore, we should choose a more accurate temperature gradient during the calculation to get a more consistent result with the reality.

4.4 Beam height

With the change of design speed of railway line, the beam height of the 32 m simply supported beam will change. For example, when the design speed of railway line is changed from 350 to 250 km/h, the corresponding beam height of the 32 m simply supported beam should change from 3.05 to 2.6 m. Therefore, it is necessary to study the impact of beam height on the vertical displacement and vertical irregularity of rail under TDL. In the calculation, heights of the beam cross section are 2.4, 2.6, 2.8, 3.05, and 3.2 m, respectively, and the results are shown in Fig. 12.

As seen from Fig. 12, with the increase of beam height, the vertical displacement of rail, irregularity versine, and alignment value, and PSD all decrease. This is mainly because no matter what beam height is adopted during calculation, the temperature gradient remains unchanged. As a result, the higher the beam section is, the smaller the rate of temperature change and vertical displacement of rail are.

From Fig. 12, beyond the value of 2.8 m, a further increase in beam height has little impact on the vertical displacement of rail and the amplitude of track vertical irregularity. Even when the beam height reaches 3.2 m, the amplitude of PSD corresponding to the 32 m wavelength nearby exceeds that of GRSLI. Clearly, under TDL, beam height is not the main factor influencing the vertical displacement and vertical irregularity of rail.

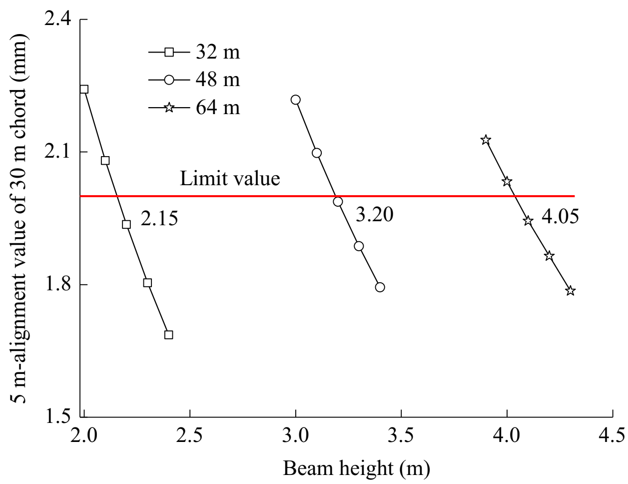

Fig. 14 Limit value of beam height

4.5 Beam span

Currently, the spans of simply supported beam bridges used in Chinese high-speed railway construction include 32, 20, 24, 48, and 64 m. Compared to the span of 32 m, the last four spans of bridge are less used. Nevertheless, the five kinds of spans above are chosen to analyze the effect of bridge spans on the vertical displacement of rail under TDL. In the calculation, we only consider the change of beam span, and assume that the beam height is fixed to 2.6 m. The results are shown in Fig. 13.

As shown in Fig. 13, with the increase of span, the vertical displacement of rail and track irregularity both increase. Especially, the vertical displacement of rail increases exponentially. When the span is up to 48 m, the corresponding 10 m-alignment value of 30 m chord exceeds the limit value. When the span is 64 m, the 150 m-alignment value of 300 m chord is also beyond the limit. In addition, with the span increasing, the wavelength whose corresponding value in track spectra exceeds that of GRSLI increases gradually (Fig. 13c).

In summary, when the beam span increases, the beam height should be raised to ensure that the irregularity caused by TDL does not overrun the limit value. At the same time, the increase of beam height can also benefit the vertical bending stiffness.

4.6 Minimum beam height

Based on the above analysis, there exists a minimum beam height which can make the irregularity caused by TDL within the limit. PSD reflects the characteristic of track irregularity in certain wavelength range, so only an individual wavelength exceeding the amplitude of GRSLI cannot signify the existence of track vertical irregularity. In addition, the sensitive wavelength of height irregularity in passenger dedicated line is also different from beam spans [21]. Therefore, the minimum beam height is determined according to the 10 m-chord vector, the 5 m-alignment value of 30 m chord, and 150 m-alignment value of 300 m chord. It is found that for the beam span of 64 m and below, if the 5 m-alignment value of 30 m chord does not overrun, the other two results will not exceed the limits. Generally, a simply supported beam bridge whose span is less than 32 m takes the same height as that of 32 m, and we only need to determine the height limits of the simply supported beams whose span are 32, 48, and 64 m, respectively. Beam height limits of different simply supported beam spans are shown in Fig. 14, where the beams are under the TDL stipulated in the Code [16]. Despite different heights and spans of beams, the TDL stays the same.

As shown in Fig. 14, the limit heights of 32, 48, 64 m spans are 2.15, 3.2, and 4.05 m, respectively. Note that these values are determined without considering structural stress, beam stability, and other factors. The heights of different beam spans, therefore, should not be smaller than the above values.

5 Conclusions

A rail-bridge-piers integrated model which could consider TDL along the vertical direction of bridge section was established and the effect of different factors on track vertical irregularity was analyzed. Some conclusions are summarized as follows:

(1) TDL along the vertical direction of bridge can cause the vertical displacement of rail, and then lead to vertical irregularity.
(2) The amplitude of irregularity caused by TDL is largely affected by the character of temperature gradient, for example, the temperature variation between the bottom and top of the bridge, the temperature curve index, and the type of temperature gradient. Therefore, in order to ensure the accuracy of results calculated by the model, parameters of temperature gradient used should be consistent with real situation in different regions.
(3) In order to ensure that the vertical irregularity caused by TDL does not exceed the limits, the beam heights of 32, 48, and 64 m simply supported box beam bridge must not be less than 2.15, 3.2, and 4.05 m, respectively.

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